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UNSTEADY LOW-REYNOLDS NUMBER AERODYNAMICS FOR MICRO AIR VEHICLES (MAVs)

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14. ABSTRACT
This report documents recent progress in in-house research in the AFRL Air Vehicles Directorate on unsteady aerodynamics at low Reynolds number. The application is the aerodynamics and flight dynamics of agile Micro Air Vehicles, to include flapping-wings. Experiments included quantitative and qualitative flowfield velocimetry on the Selig SD7003 airfoil, undergoing a range of harmonic and ramp motions in two degrees of freedom - that is, pitch and plunge. Relevant classical results in the literature have been confirmed, with new results on spanwise flow in the starting-vortex for plunge motions of high reduced frequency.

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Summary and Motivation

As interest in Micro Air Vehicles (MAV) applications continues to advance, AFRL needs to be at the forefront of MAV *aerosciences*: aerodynamics, fluid-structure interactions, flight controls and flight dynamics. Batteries, materials, sensors, actuators, communications and related technologies will advance in their own right, while other organizations – in the DoD and elsewhere – are active in MAV systems sciences, such as field demonstrations of today's state-of-the-art. Arguably, the principal challenge in MAV aerosciences is not efficiency enhancement (drag reduction, range/endurance increase) but mitigation of gusts and increase of flight agility, requiring attention to the unsteady aerodynamics of massive separation, in a combined experimental-computational-theoretical approach. The present work pursues the experimental route under the "In-House Development Program" (IDP), focusing on high reduced-frequency 2DOF airfoil and wing unsteady aerodynamics. In 2007 classical results on dynamic stall and steady-state laminar separations were extended to a range of pure plunge cases, with preliminary exploration of mixed pitch-and-plunge as models of flapping-wing flight and gust response. Addition of direct force-measurement capability is ongoing, with extension to low-aspect-ratio planforms and eventually to flexible wings. The overall theme is exploration of transient response – in terms of MAV maneuverability and the inverse problem of gust response.

This report documents in-house research at AFRL/VAAA. It is supported by the following publications:

1. Kaplan, S., Altman, A., and OL, M. "Wake Vorticity Measurements for Low Aspect Ratio Wings at Low Reynolds Number". Journal of Aircraft, vol.44 no.1, pp. 241-251, 2007.
2. OL, M. "Vortical Structures in High Frequency Pitch and Plunge at Low Reynolds Number". AIAA-2007-4233, 2007.

Progress in 2007

In 2007, the 2nd and concluding year of the IDP (the funding formally ends 30 September 2007), work focused on particle image velocimetry (PIV) and dye-injection experiments in the SD7003 airfoil, the latter borrowed from prior steady-case experiments[1]. The "High-Intensity Pitch/Plunge Oscillator" (HIPPO) rig was designed, built and installed in the AFRL/VA "Horizontal Free-surface Water Tunnel" (HFWT) in 2006, in the first year of the IDP. The research campaign in 2007 was primarily to:

1. Conduct proof-of-concept unsteady airfoil measurements, comparing PIV data for example with those of Radespiel[2].
2. Conduct a Reynolds number and reduced-frequency parameter study to assess how much mismatch between computations and experiments is acceptable for validation of low-Re airfoil wakes. Test cases were motivated by results of Lai and Platzer[3].

3. To assess spanwise flow and spanwise nonuniformities for nominally 2D problems.
4. To consider cases of unequal pitch and plunge frequency, as models of gust response for flapping-wings.
5. To build a research group based on AFRL/VA co-ops and local faculty collaborators.

These objectives were largely met during 2007. A pure-plunge case with reduced frequency $k = \pi fc/U_\infty$ is examined in Figure 1, with velocity and vorticity plots for four phases of the cosine wave, with corresponding induced angles of attack as shown in the figure. Vorticity contour plots reveal a double-vortex structure, which convects downstream at approximately the free-stream speed. This is consistent with classical high-Reynolds number dynamic stall, at much lower reduced frequencies[4]; specifically, one sees not a leading edge vortex shedding per se, but a wall-bounded downstream progression of the double-vortex. Mean-velocity contour plots show the beginning of the shed vortex train aft of the trailing edge at $\varphi = 0.25$, present together with a strong leading edge suction peak.

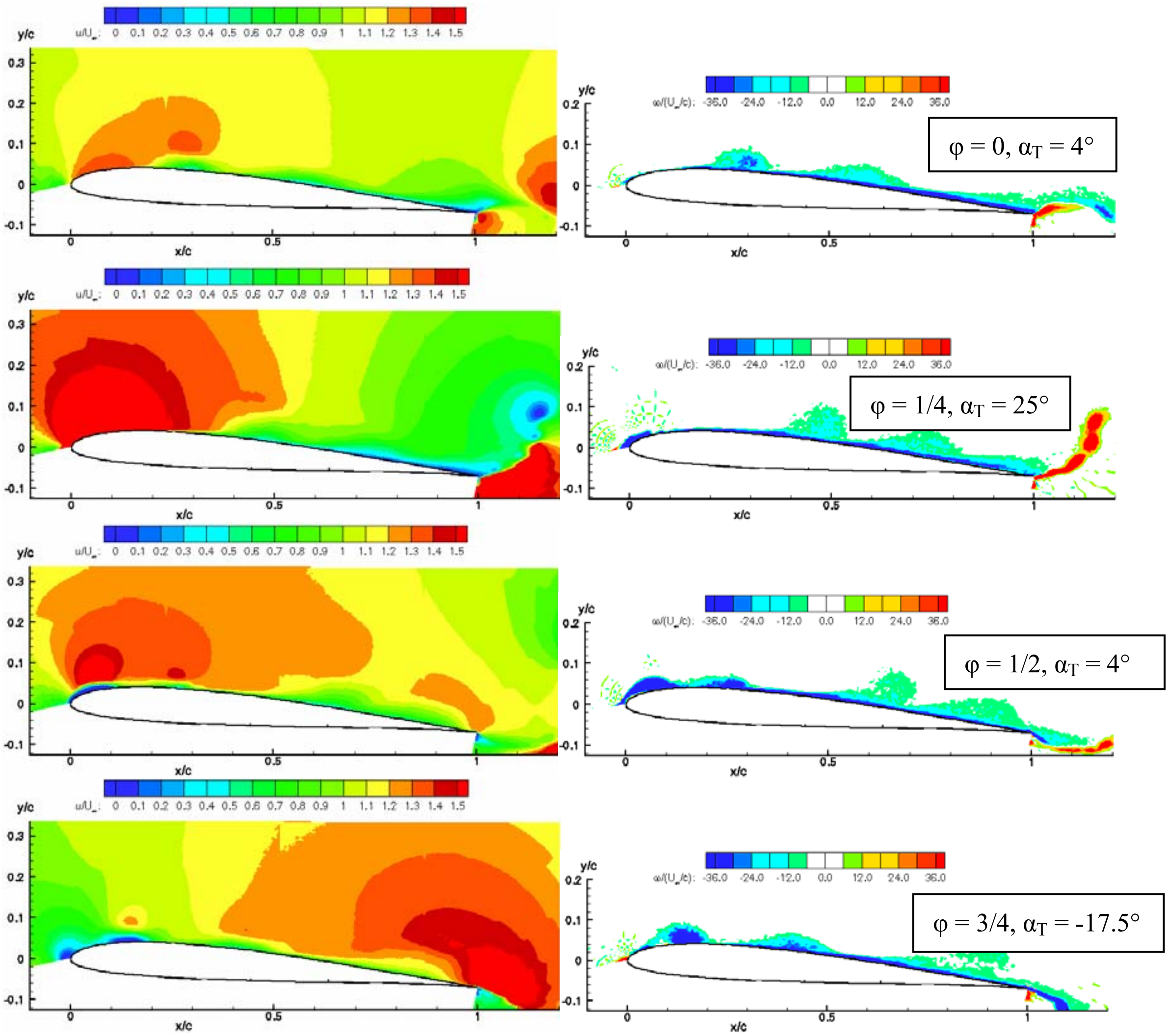
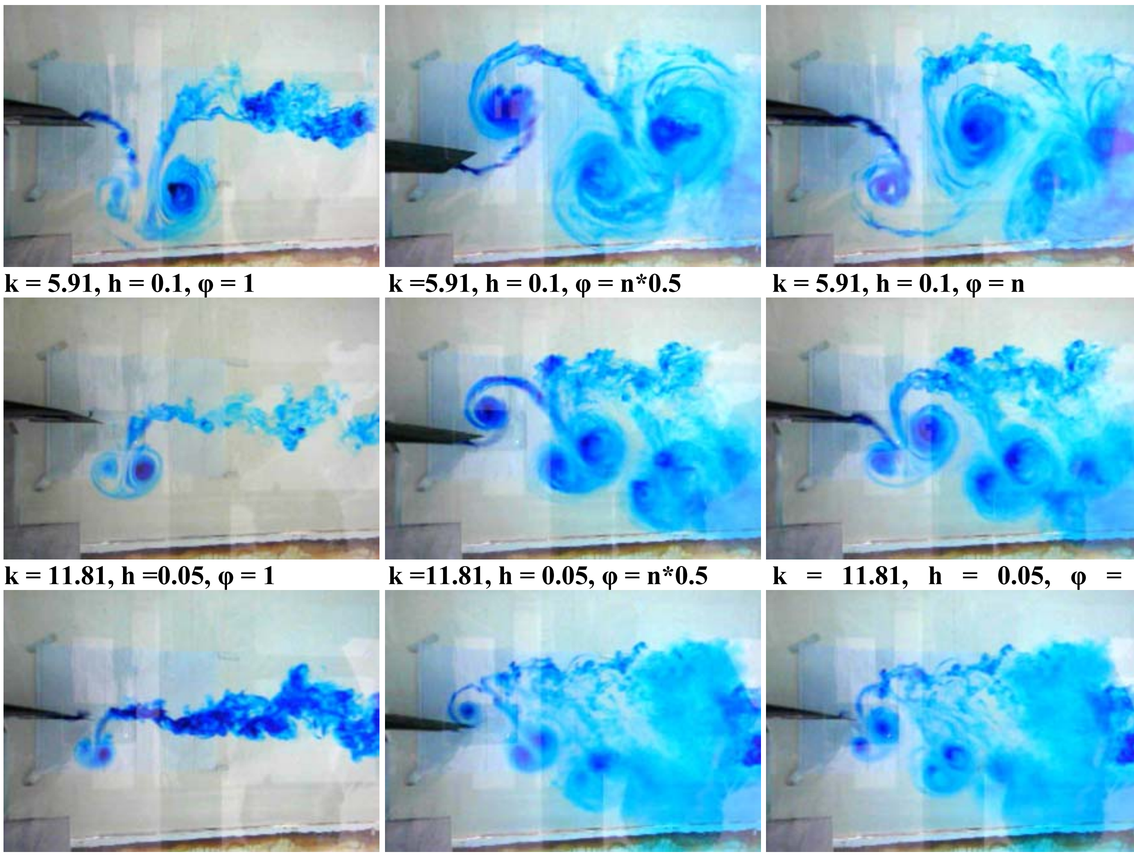


Figure 1. ***k*** **= 3.93 pure-plunge, contours of phase-averaged (115 realizations) normalized streamwise component of velocity, and phase-averaged out-of-plane vorticity component, after periodic conditions established; from top to bottom, phases are φ = 0, 1/4, 1/2 and 3/4.**

These results raise the question of how low Reynolds number high-frequency unsteady phenomena differ from the better-known helicopter applications at much higher Re and O(10) times slower dimensionless rates. Subsequent work will consider even lower Re and higher dimensionless rates of motion, as well as combining pitch and plunge, for a range of pivot locations. These changes are expected to show convincing departure from the classical dynamic-stall case, although definitive elucidation of insect high-lift mechanisms will probably not be achievable in the near term.

Most prior work in low-Re unsteady airfoils has been for symmetric airfoils at zero mean angle of attack, motivated by aquatic animal propulsion or fundamental fluid mechanics investigations. One of the objectives of the present study is to consider low-Re-relevant airfoils, with camber, and with nonzero mean angles of attack, at reduced frequencies relevant to examples in nature – dragonflies, hummingbirds and the like. The present experiments are viewed by the PI as 2D analogues of 3D experiments and computations

conducted elsewhere under AFOSR sponsorship. The relation between 2D and 3D phenomena is important to quantify in a systematic way. 2D experiments and especially computations are much more tractable, and therefore more suitable for parametric analysis. It is therefore desirable to ascertain what aspects of the startup vortex problem, for example, are irreducible from 3D to 2D. Of course, this also has implications for longstanding discussions on unsteady lift production mechanisms exploited in particular by insects[5].



k = 5.91, h = 0.1, φ = 1 | **k =5.91, h = 0.1, φ = n*0.5** | **k = 5.91, h = 0.1, φ = n**

k = 11.81, h =0.05, φ = 1 | **k =11.81, h = 0.05, φ = n*0.5** | **k = 11.81, h = 0.05, φ = n**

k = 23.62, h = 0.025, φ = 1 | **k =23.62, h = 0.025, φ = n*0.5** | **k = 23.62, h = 0.025, φ = n**

Figure 2. Pure-plunge, Re = 20,000, mean α = 4°; three cases of kh = 0.591, and three motion phases: φ =1 after start-up (top of stroke), bottom of stroke in established flow, top of stroke in established flow.

Strouhal number, proportional to the product of reduced frequency and reduced amplitude, has been shown as the discriminator between a net thrust-producing and net drag-producing wake for airfoil plunge[3]. Several examples in the literature note, however, that the size of the wake scales not with Strouhal number itself but with reduced amplitude, h. This was confirmed in the present study for thrust-producing values of St (Figure 2), for both start-up transients and established periodic motion.

Another focus of 2007's research was consideration of start-up transients, since it is the time scales associated with these transients that are important for MAV maneuvering and gust response. An example is Figure 3, showing that with increasing reduced frequency

there is considerable increase in axial (spanwise) flow in the core of the starting-vortex. To the PI's knowledge this is a new result, and merits further investigation by stereoscopic PIV and by computations in 2008.

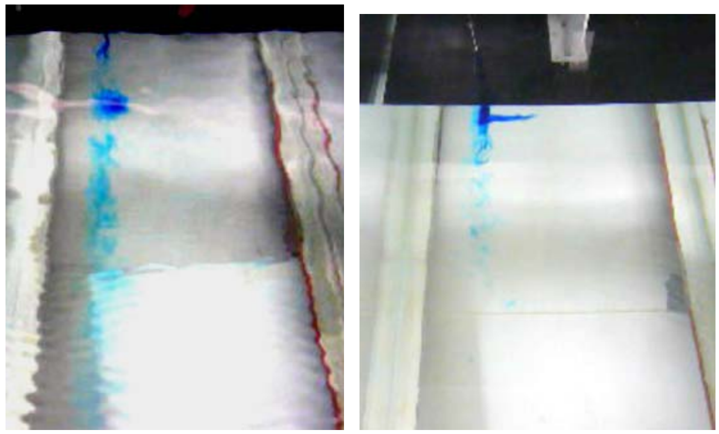


Figure 3. k = 3.93 (left) and k = 11.81 (right) pure-plunge, Re = 20000, h = 0.05. Note the difference in spanwise flow in the starting vortex, visible in the upper left-hand of each picture. Also note the difference in how far the starting vortex has convected downstream of the trailing edge.

Beyond extensions to higher frequency and lower Reynolds number, the next step in IDP in-house research, with the hope of transitioning to AFOSR core-funding in 2008, is progression from 2D airfoils to 3D wings (aspect ratio = 1 and 2 rectangles), with concomitant increase in the complexity of the flowfield diagnostics necessary to resolve these flows. We will consider an airfoil (first a flat plate of 2% thickness, then an S-curve) more relevant to practical considerations at insect Reynolds numbers. The intended models will eventually be tested in both rigid and flexible form. The rigid case will be the dynamic analog of the static case, as discussed in the first of the publications mentioned above. The introduction of structural flexibility raises issues of aeroelastic scaling, which the PI is addressing with his university faculty collaborators and colleagues in AFRL/VA.

Academic Collaborations

An important component of this work is collaboration with faculty and graduate students in the low Reynolds Number aerodynamics community. This includes computations and experiments, with collaborations on experimental-computational comparison, experimental technique, elucidation of canonical problems relevant to Micro Air Vehicle applications, and conceptualization of analytical approaches to estimating time-dependent aerodynamic loads. Ongoing collaborations are summarized below.

Prof. Ashok Gopalarathnam (North Carolina State University), as the university collaborator funded by the IDP, is studying the analytical and low-order numerical analysis aspects of unsteady airfoil aerodynamics. On the analytical aspect, he is applying complex-variables approaches for developing analytical solutions to airfoils oscillating in pitch/plunge motion. On the computational , currently running calculations on the pure-plunge case shown above. As a follow-on Prof. Gopalarathnam will consider small

chord-fraction high-frequency trailing edge flaps as a flow control device, to modulate vortex shedding in the near-wake. This will be approached as a model for gust attenuation.

Prof. Aaron Altman (University of Dayton), with partial funding from the Air Vehicles Directorate in-house budget, is using the HIPPO rig to study the vorticity balance in a range of hovering motions, using the HFWT as a quiescent tank.

Profs. Wei Shyy and Luis Bernal (University of Michigan) are running computations and experiments, respectively, in parallel with pure-plunge and pitch-plunge cases investigated in-house at AFRL/VA. Prof. Bernal and the PI are collaborating on a fiber-Bragg grating optical load-cell approach to direct force measurement, for time-synchronized comparison with vortex structures elucidated via PIV. The University of Michigan collaborations leverage an ongoing STTR and a MURI starting in the summer of 2007.

Prof. Haibo Dong (Wright State University) is collaborating with HFWT experiments using immersed boundary method computations, on a test program developed jointly with AFRL/VA. The ultimate objective is gust-response modeling for flapping-wing MAVs in 2D and 3D.

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